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1. The enclosed paper, "Meteorological Satellites", prepared by Dr. Morris Tepper, Director, Meteorological Systems, is approved for external publication in accordance with Paragraph 4-b of NASA Management Instruction 25-1-2.

2. This paper will appear as a chapter in the book, Space Exploration, being published by McGraw-Hill Book Company. The anticipated publishing date is Fall 1963.

Leonard Jaffe for
Morton J. Stoller

Enclosure -
As noted above

...to NASA Offices and
NASA Centers Only

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METEOROLOGICAL SATELLITES*

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National Aeronautics and Space Administration, Washington, D.C.

(NASA TM X-50305)

This paper will appear as a chapter in the book Space Exploration being published by McGraw-Hill Book Company. The anticipated publishing date is Fall 1963.

Submitted for Publication

* Presented in December 1962 as Lecture #13 in the "Space Exploration" series given by the Engineering Extension and Physical Sciences Extension, University of California, Los Angeles. The factual material contained herewith is available through the regular technical information sources of NASA. The opinions expressed in this document do not necessarily represent the official position of the National Aeronautics and Space Administration.

SECTIONS

1. Meteorology as a Scientific Discipline

This chapter deals with meteorological or weather satellites - the discussion includes some detailed information on the technical and operational aspects of these satellites; the capabilities of these satellites are assessed; both the contributions of these engineering developments and their limitations are considered. An attempt is made to answer the question of why as well as what and how.

It will be fruitful first to dwell momentarily on the more general topic of meteorology as a scientific discipline. It will then be the objective to consider the role of meteorological satellites within that scientific discipline. Now, what are the elements of a scientific discipline?

There are essentially four important elements. They are (1) observing, (2) analyzing, (3) explaining, and (4) testing.

These four elements usually combine in a sequence in somewhat this manner. A set of observations is taken. By grouping the observations properly we are able to describe some phenomenon. This process is called analysis. In turn these descriptions lay the foundation for an hypothesis to explain, through cause and effect how these phenomena came about. Finally, the hypothesis (or explanation) is tested in essentially one of two ways:

(a) We consider a set of observations and see if the events subsequent to these observations follow from the proposed theory.

(b) We bring about our own initial conditions and see if desired results follow as indicated from the proposed theory.

Of these four elements, the scientist is most concerned with the third - explaining. It is through this operation that his knowledge of the universe increases.

In meteorology, however, an anomalous situation exists. Although the meteorologist, as an atmospheric scientist, is essentially interested in explaining nature, he finds that the fourth operation of his science, testing, has such remarkable and useful social and economic application and political implication, that it replaces explanation in the dominant role of the science of meteorology. With regard to testing, note the words used above:

(a) We consider a set of observations and see if the events subsequent to these observations follow from the proposed theory -- so far as meteorology is concerned this is the essence of weather forecasting.

(b) We bring about our own initial conditions and see if desired results follow as indicated from the proposed theory -- so far as meteorology is concerned this is the essence of weather control.

Thus, the importance of these applications (weather forecasting, and weather control) has focused attention on the testing operation of the meteorological science discipline and has made it an end unto itself. Thus, meteorological theory is considered inadequate if it only explains; for it must also be applicable to weather forecasting and must also lay a groundwork for eventual weather control.

Nevertheless, despite the importance of these applications, we must keep in mind that they follow a more or less orderly sequence in the scientific method, wherein first comes observing, then analyzing, then explaining and finally testing (prediction and control). But first comes observing.

2. Meteorological Observations

Man lives on the bottom of a vast "ocean" of air. This atmospheric ocean covers the entire globe and extends upward with diminishing density. This atmospheric ocean is in constant motion, its properties changing constantly. Earlier scientists soon recognized that particular atmospheric motions produced particular patterns of weather and so it became necessary to observe and describe the basic atmospheric motions.

The first weather charts covered an area of only a few thousand square miles and were restricted to surface observations taken more or less simultaneously at prescribed times. The more these charts were studied and used as a basis for weather analysis, hypothesis and prediction, the stronger became the realization that knowledge of the interaction of atmospheric processes vertically and horizontally over hemispheric dimensions was required in order to understand fully meteorological motions and their time variations. Out of this realization there developed the existing world radiosonde network, covering many land areas, islands and oceanic shipping routes (Fig. 1). Each station in this network is an upper air observing station. Twice (and at some locations, four times) daily a balloon carrying observing equipment is sent aloft and the sensors telemeter back information on atmospheric pressure, temperature and moisture. This vertical sampling of the atmosphere is effective to about 100,000 ft elevation. Recently with the advent, development and use of the meteorological sounding rocket, measurements are also being made from time to time and at very few locations, of the upper one percent of the atmospheric mass, beyond the reach of the radiosonde balloon.

The distribution of the existing stations is dictated by external conditions. These stations are by and large manned and consequently are located primarily in areas where human residence is feasible. This limitation has produced a totally inadequate network. Fig. 2 is taken from a report of a special network study commission of the World Meteorological Organization. Essentially, it shows that 90% of the earth's surface has an inadequate number of upper air observing stations. This map shows the earth divided into 100 equal areas, and gives the number of existing upper air stations within each area. Twenty stations are considered the required number for sufficient upper air coverage. There are only 11 areas with this sufficient upper air observational coverage (20 stations or more); 10 areas with marginal coverage (10-19 stations);

29 with less than minimum coverage (3-9 stations) and 50 areas with totally inadequate upper air observational coverage (less than 3 stations).

Although the radiosonde observations are supplemented by other upper air observations (small wind-measuring balloons, radar observations, aircraft observations, and others) these other observations are few in number and do not materially alter the picture.

On the other hand, it is generally agreed by the meteorologist that what is required is the measurement of the horizontal wind components, pressure, temperature, and water vapor content as well as the concentration of the principal absorbers and emitters of radiation (CO_2, H_2O and O_3) at every 5° grid of latitude from the surface up to 100,000 ft elevation.

Why must we have so many observations?

A first answer is almost obvious. It follows from the discussion so far. You can't control the behavior of a phenomenon unless you are able to predict it accurately. You can't predict the future of a phenomenon unless you understand it. You can't understand or explain a phenomenon unless you can describe it. You can't describe a phenomenon unless you observe it quantitatively. And the above is the number of observations required.

We can become a little more specific if we regard the weather forecasting processes a little more closely. (It is not possible to consider the weather control processes in the same manner due to the very limited knowledge about them at this time).

3. Approaches to the Weather Forecasting Process

There are essentially four basic approaches to the atmospheric prediction process. They are:

a. Analogue approach. The historical file of weather maps is searched for a specific case which is identical or similar to the weather situation today. The events that followed the prototype in the past form the basis for the forecast of tomorrow's weather.

b. Statistical (objective) approach. Significant statistical correlations and probabilities are sought relating values of weather parameters on one day with weather events subsequently.

c. Physical (empirical) approach. Physical reasoning usually based on past experience is used to predict how weather systems will move and what weather will be associated with them. Persistence, or the tendency of weather events to continue more or less unchanged, is frequently used in this empirical approach.

d. Dynamical (numerical) approach. A series of simultaneous equations are established which describe the physical nature of the atmosphere. These equations include the (1) laws of conservation of momentum, (2) the law of conservation of mass, (3) an energy equation, and (4) the gas law.

The system is a series of partial differential equations involving partial derivatives both with respect to time and space coordinates. Mathematically, if the initial conditions are known and if the boundary conditions can be specified, it is possible to solve for the atmospheric variables as a function of time. This, of course, is just another way of saying that the atmosphere is amenable to "deterministic prediction". With the recent availability of high speed electronic computing machines it is now possible to attempt the solution of these equations in a reasonable period of time.

In each of these forecasting processes there is required an accurate knowledge of the existing atmospheric conditions -- "the initial conditions". The fourth approach and the others to a lesser degree, also requires a knowledge of the effects of external forces -- the boundary conditions.

We have seen that the conventional meteorological observations are totally inadequate in providing this required information. Yet, the meteorologist has been trying to predict atmospheric events without having this adequate knowledge. It is as if a doctor were requested to make a diagnosis and a prognosis of patient's condition while viewing only some 10-15% of the patient's body. At times and under special conditions this might be possible and by exceptional physicians.

And indeed there are exceptional forecasters as there are exceptional physicians. However, by and large this is a poor situation and one which we must correct.

4. Meteorological Satellites

Meteorological satellites are global observation platforms which have the potential for contributing observations of both the initial conditions and the boundary conditions.

Meteorological satellites are observation tools. In and by themselves, they furnish neither weather analyses nor weather predictions. But they are powerful observation platforms. Several types of observations have been suggested as possible by means of satellites: (1) cloud cover, (2) heat budget measurements, (3) temperatures, (4) precipitation, and (5) atmospheric constituents.

This list differs appreciably from the one listed earlier as required by the meteorologist. This difference merely reflects our current technological limitations. This particular list of measurements has been proposed simply because there exists some idea of the instrumentation that will produce them: cameras can observe cloud cover, electromagnetic radiation measurements (principally in the visible and IR bands) can provide heat budget measuremants, a spectrometer - temperatures, radar - precipitation, UV - possibly O_3. To date the meteorological satellites have been successful in providing observations of the first two on this list.

The limitation of meteorological satellites to viewing the atmosphere only at a distance limits severly the kinds of instruments possible on board - and these are essentially devices for measuring the earth's atmosphere radiation in portions of the electromagnetic spectrum. Recently, it has been proposed to use satellites as data collection vehicles which interrogate remote sensing platforms. With this extention of the satellite capability it will be possible some day to acquire the more specific kinds of observations required, in situ. The discussion here will continue with the meteorological satellite as a sensing platform and its current successes and future plans.

5. Early Milestones in the Development of Meteorological Satellites

Significant events preceded the development of meteorological satellites of today as important atmospheric observation platforms. It is no surprise that these beginnings had their roots in the observation of the atmosphere by means of instrumented rockets.

a. March 7, 1947 -- The first successful series of photographs of the earth's cloud cover was taken on this date by means of a V-2 rocket launched over White Sands, New Mexico. A camera containing film took the photographs from an altitude of 70 to 101 miles. The film was recovered after the flight.

b. These photographs (Fig. 3) were analyzed for their meteorological content by D. L. Crowson who suggested that rocket photography of clouds would become commonplace as did aircraft observation when that system was introduced. He suggested observation by means of television and the transmission of the data, to do away with film recovery. Since the rocket was fired in essentially good weather, the meteorological phenomena reported by Crowson were not particularly exciting.

c. In the period 1947-1950 there were additional experiments of high altitude cloud photography utilizing V-2, Aerobee and Viking series of sounding rockets conducted at White Sands. In 1951 probably drawing on the experience gained in analyzing these data, S. Greenfield and W. W. Kellogg made the first serieus proposal for meteorological satellites in a RAND Corporation classified paper. Most of the principles and suggestions of this paper still apply today.

d. The earliest public discussion for requirements and observations of meteorological satellites was held in 1954 by H. Wexler and a recent analysis by W. K. Widger comparing Wexler's depictions with actual TIROS cloud observations, demonstrated that generally Wexler had prophetic insight into the potential observations of satellites.

e. A major and dramatic impact on the scientific community demonstrating the unpredicted value of high altitude cloud photography was the 1955 paper "A Rocket Portrait of a Tropical Storm" by L. F. Hubert and O. Berg In this paper, the authors analyze the pictures taken over the southwestern U.S. by a V-2 rocket on

October 5, 1954. The pictures show the presence of a circulation describing a storm which had passed onto the land from the Gulf completely undetected by the conventional network of observing stations. This discovered storm explained the hithertofore unexplained heavy rains in several inland stations. This ability of detecting otherwise unknown storms by means of high altitude photography was to be repeated over and over again by means of the TIROS picture data.

f. During the second half of the 1950's there was considerable serious planning and activity towards the development of a meteorological satellite capability. On February 17, 1959, the first successful meteorological satellite was launched -- Vanguard II. However, it was successful only in this sense: The satellite went into orbit and its sensory and telemetry systems transmitted data that were received on the ground. However, these data were never reduced. Vanguard II was a 20-pound, 20-inch sphere developed by the U.S. Army Research and Development Laboratory at Ft. Monmouth. It contained two photocells, sensitive in the .6-.8μ range, which alternately scanned the earth. Upon injection the satellite developed a serious (but known) wobble and the scan lines were no longer parallel. Although theoretically it is possible to reconstruct the data, the much better data available from the TIROS series have made this effort unwise.

g. The first pictures from a space satellite of the earth's cloud cover was from Explorer VI -- the "Paddlewheel" experiment launched on August 7, 1959, from Cape Canaveral. This 142-pound satellite contained an elementary image scanning TV system. Its resolving capability was so very poor that only one such set of data were reduced (Fig. 4). While on the one hand they did show the possibilities of TV observations from space, the results were terribly discouraging.

h. On August 24, 1959, a recovered nose cone from an Atlas missile produced pictures taken over the Caribbean Sea and the Atlantic Ocean. Although this was a film system and not a TV system, the pictures again fired the imagination of the meteorologists. Using these pictures the analysts at the Geophysics Research Laboratories and the Weather Bureau, reconstructed a tremendous amount of information about the atmosphere and its structure. The goal now became to improve the TV system to yield similar results.

i. On October 13, 1959, Explorer VII, a 92-pound satellite was successfully launched. In addition to other experiments it carried a radiation balance experiment devised by V. Suomi to measure the thermal radiation balance or "heat budget" of the earth. The experiment contained (1) two hemispheres, coated black, equally sensitive to both solar and terrestrial radiation, (2) one hemisphere painted white, more sensitive to terrestrial radiation than to direct and reflected solar radiation, (3) one with a polished gold surface more sensitive to direct and reflected solar radiation than to terrestrial. The temperature measured by each sensor is dependent on the amount of radiation present to which it is sensitive. The calculation of the earth's heat budget from these data is long and tedious when done by hand and a computer method is being developed. Suomi has published some of these data and shown interesting correlations with atmospheric processes.

j. On April 1, 1960, TIROS I was launched from Cape Canaveral (Fig. 5) and for 78 days it transmitted 23,972 pictures of the earth's cloud cover of which about 60% or over 13,000 were useful.for meteorological purposes. The performance of TIROS I was so much better than had been expected from previous efforts that meteorologists were quick to recognize that a new era in the observation and study of weather processes had just begun.

6. The TIROS System

To date there have been six attempts to launch a TIROS satellite into orbit, and each attempt has been successful. In describing the TIROS system one is not really describing any one satellite since in this research and development program, changes have been made from one spacecraft to the next, so that in fact, no two satellites have been exactly the same.

a. The Spacecraft. The TIROS spacecraft (Fig. 6) is shaped like an 18-sided hat box. It is 22 inches high and 42 inches in diameter. The sides and the top of the spacecraft have 9,120 solar cells which provide electrical power for 63 Ni-cd batteries. Over 1/4 of its 280 odd pounds is structural weight. An 18" receiving antenna protrodes from the top and at the bottom are four 22" transmitting antennas spaced 90° apart.

b. The TV Camera System. The heart of the TIROS system consists of two independent television camera systems. Although three systems are described below, only two were flown at any one time. One camera has a wide angle - 104°-lens, capable of photographing an area in excess of 600,000 square miles, or a square area of about 750 miles on each side when the satellite is looking vertically downward. This wide angle lens has been a feature of each TIROS satellite. A second system (used in the last 3 TIROS) uses a medium angle - 76° lens, capable of photographing an area of about 232,000 square miles or a square area of about 450 miles on each side when the satellite is looking vertically downward. The third system uses a narrow angle - 13° lens, capable of photographing an area of about 5,000 square miles or a square of about 70 miles on each side where the satellite is looking vertically downward. The cameras use 1/2" vidicon tubes, and has the additional properties as given in the accompanying Table I.

(Table I)

As part of each camera system there is a tape recorder which with its 400 foot long tape can record up to 32 pictures during an orbit. The two camera systems can be operated separately or simultaneously. Operation of the cameras is based on commands sent from ground stations which set timers in the satellite to trigger the cameras when the satellite passes over an area from which photographs are desired and possible - then when it is within range of the ground stations, readout occurs. Complete ground station readout of the tape from each camera takes about 3 minutes. The processes automatically erases the tapes.

In addition to this "storage mode" of operation, the cameras can be directed to take pictures and transmit them directly to the acquisition station, by-passing the tape recorder entirely. This is only possible when the satellite is in line of sight of a Command and Data Acquisition Station and when picture taking conditions are feasible.

c. The "Control" Systems: Several basic control systems are integrated into the TIROS spacecraft.

(1) De-Spin Mechanism: At injection, the satellite is spinning at about 125 rpm. To permit the cameras to take pictures without smearing, this rate must be reduced appreciably, to 9-12 rpm. About 5 minutes after payload separation, a pair of 1-pound weights at the end of a light steel cable are unwound from around the base of the satellite and cast off.

(2) <u>Spin-up Rockets</u>: To maintain the satellite spin rate and overcome the spin rate decay caused by the earth's magnetic drag on the satellite several pairs of small solid fuel rockets positioned on the base plate are used (Fig. 7). Diametrically opposite pairs can be fired on ground command.

(3) <u>Precision dampers</u>: Inside the spacecraft two diametrically positioned weights are permitted to slide on curved tracks parallel to the spin axis. This oscillation overcomes any tendency to wobble.

(4) <u>Horizon scanner</u>. This is an infrared sensor mounted on the rim of the satellite with a view at right angles to the spin axis. It measures the ratio of time it looks into space as compared to the time required to scan the earth. This ratio is a function of the spin axis attitude.

(5) <u>North indicator</u>: This sensor consists of 9 solar cells equally spaced around the sides of the satellite by means of which it is possible to determine the position of the satellite with respect to the sun.

(6) <u>Magnetic Attitude control</u>: This system consists of a wire coiled around the lower portion of the spacecraft by means of which it is possible to generate a controllable magnetic field around the satellite.

This induced magnetic field reacts with the earth's magnetic field and produces a torque. Thus, it is possible to position the satellite gradually on command from a ground station to obtain the most advantageous angle for picture taking and to position solar cells for recharging the batteries.

d. IR Radiation Experiments: There are three IR radiation measurement experiments -

(1) Five channel radiometer: Five infrared detectors are oriented 45° to the spin axis and scan through a combination of the satellites rotation and its movement along the orbit. The spectral bands and objectives of the measurements to be derived from these detectors are: (Fig. 8)

a. 6.3 μ - radiation from top of water vapor band

b. 8-12 μ - atmospheric "window" (measures radiation from cloud tops, or in the absence of clouds from the earth's surface)

c. 0.2-5 μ - earth's albedo

d. 7-30 μ - radiation of earth and atmosphere

e. 0.5-0.7 μ - visual range

(2) Wide field (non-scan) radiometer: This consists of 2 sensors one white and the other black which together measure the heat balance of the area of the earth

viewed by the TV camera. The white body measures the heat radiation from the earth while the black body measures both visible (reflected solar radiation) and heat radiation.

(3) Omnidirectional radiometer (U. of Wisc.): As in the above experiments, this sensor also measures the gross heat budget, except that the data, although of lower resolution, is more continuous since the sensors view the earth almost all of the time.

Data from the infrared experiments are recorded continuously on magnetic tape for playback of the last orbit's data on command from one of the ground stations.

e. Ground Stations

(1) Tracking stations: The satellite's beacon transmitter carrier is tracked by means of the regular U.S. Global Minitrack Network.

(2) Command and Data Acquisition Station: There are two primary stations which command the satellite to take observations and then receive the satellite's transmission of these data. About eight out of the possible 14 orbits per day are acquired by these primary stations. The TV data received at these stations are displayed on kinescopes and photographed by 35 mm cameras. Meteorological teams analyze these data and relay them to the U.S. Weather Bureau at Suitland.

The following table shows the primary, backup and auxiliary CDA stations. (The Santiago station was installed after TIROS III to provide more flexibility in choosing an orbit to be read out - it does not acquire any data.)

(Table II)

f. The Launch Vehicle: TIROS I was launched by the Thor-Able launch vehicle and all the remaining five satellites by the Thor-Delta.

For a minute and a half after lift-off, Delta is guided by its Thor booster, a Bell Telephone Laboratories radio guidance system makes refined velocity and steering corrections as needed. Shortly after first stage burn-out and separation, and after ignition of the second stage, the fairing -- covering the third stage and the TIROS payload -- is jettisoned.

Second stage burning ends about four and one-half minutes after lift-off. The vehicle, with second and third stages still attached is now at an altitude of about 125 miles. At this point a six-minute coasting period occurs. During this period, guidance is provided by a 42-pound flight control system contained in the second stage. The satellite and the third stage are spin stabilized by small rockets mounted on a "spin table" between the second and third stages. At the end of the coast period -- about ten minutes after launch -- the second stage separates, and third stage ignition occurs. Soon the required orbital velocity of 17,000 miles per hour is reached and the satellite, trailed by the third stage, is injected into orbit.

7. The First Six TIROS Launches

a. TIROS I: The TIROS I spacecraft was launched from the Atlantic Missile Range on April 1, 1960. During its 78 days of operation, until June 17, 1960, TIROS I transmitted almost 23,000 cloud cover photographs. As a pioneer spacecraft in the meteorological satellite program, TIROS I opened a new era in weather observation by providing data covering vast areas of the earth which were previously not available to weathermen and weather research programs.

b. TIROS II: TIROS II was placed into orbit November 23, 1960, and provided more than 36,000 photographs of cloud cover. Its operational lifetime far exceeded initial estimates and photographs from the spacecraft's TV cameras were received through November 1961. Photographs of ice pack conditions in the Gulf of St. Lawrence proved that weather satellites could locate ice boundaries in relation to open seas. In addition, data provided by the satellite was used by forecasters for the suborbital flight of Alan B. Shepard, Jr., in May 1960, and the launching of Ranger I two months later.

c. TIROS III: The TIROS III spacecraft, launched July 12, 1961, added further milestones to the TIROS record, particularly in the detection of tropical storms. All six of the hurricanes of the 1961 season were observed by TIROS III. Hurricane Esther was detected by the satellite two days before it was observed by conventional methods. TIROS III provided information which resulted in 70 storm advisories being issued. These were sent to weathermen in the Far East, Latin America, the Indian Ocean and the Continental U.S. In addition, its data led to adjustments in 76 National Weather Satellite Center analyses.

TIROS III photographs were used to support Project Mercury, Ranger, the Air Force's Discoverer satellite series, the firing of Long Tom meteorological rockets in Australia and the Navy's 1961 Antarctic resupply mission. Use of TIROS III data was discontinued in the Fall of 1961 because of loss of contrast in its photographs. During its lifetime, TIROS III transmitted more than 35,000 cloud cover photographs.

d. TIROS IV: The TIROS IV spacecraft was launched on February 8, 1962, primarily to continue earth cloud cover photo coverage and to confirm its capability as an ice reconnaissance vehicle. Under Project TIREC - TIROS Ice Reconnaissance - a joint U.S. Weather Bureau-U.S. Navy-Canadian government project, aircraft took photographs while flying the predicted path of the TIROS. These photographs were compared with those taken by the TIROS and it was concluded that the photography provided by TIROS was a better means of ice study over large areas than the conventional aircraft reconnaissance method.

TIROS IV was also used in an Air Force project called Bright Cloud to develop a cloud identification system based on shape and brightness by using TIROS photographs.

During its operational lifetime which lasted until June 12, the fourth TIROS satellite transmitted 33,000 cloud cover photographs. Information it provided resulted in issuing 102 storm advisories. Seventy-nine adjustments in National Weather Satellite Center analyses were also made based on TIROS data.

e. TIROS V: The fifth TIROS was launched June 19, 1962, in conjunction with the 1962 hurricane season. Although its medium-angle camera malfunctioned on July 6, to date TIROS V has observed all tropical storms -- both hurricanes and typhoons -- which have occurred. It gave first warning on half of the world's ten most serious storms in August. As of December 2, 1962, more than 38,000 photographs have been transmitted by the TIROS V. It is still transmitting.

f. TIROS VI: TIROS VI was launched on September 18, 1962, to insure that hurricane season would be adequately covered should the second camera aboard TIROS V fail. Since TIROS V,continues to function properly we have had two satellites in operation with the additional coverage. As of December 2, 1962, more than 28,000 photographs have been transmitted by TIROS VI.

The following tables list the primary physical characteristics of each of the TIROS satellites and significant launch data associated with each satellite.

(Table III)

(Table IV)

8. Results to Date

With this as a background, what can be said has been accomplished to date with these six successful launches.

a. First, the TIROS launches have demonstrated that a spacecraft and supporting ground system could be developed around special sensors like the dameras and infrared radiation detectors, and could transmit the measurements of these sensors to the earth with satisfactory fidelity. In general, one may say that the quality and quantity of the end product may be considered an excellent indication of the success of a system. The more than 190,000 pictures taken by the six TIROS satellites (as of December 2, 1962) bear convincing testimonial of a successful TIROS system operation. In addition, the radiation data gathered by the TIROS II, III and IV satellites cannot be measured in individual pictures and frames but rather in about 2,000 14-inch reels of tape containing interesting and useful measurements.

This excellent system performance involves the successful operation of many interdependent and delicate subsystems, components and electronics. Fig. 9 is an example of the type of equipment required in this operation. It is a photograph of the infrared electronics equipment. From left to right, it shows the power supply, the tape recorder, the main deck electronics, the 2-watt transmitter and the motor electronics all of which fit into the canister in the back. If you consider that the canister is only 15 inches tall, you can realize the dense packing of electronics and the extent of microminiaturization that had to be done.

In several instances new and previously untried technological advances had to be made. Fig. 7 shows spin rockets attached to the baseplate of the satellite. These are fired in pairs whenever an additional spin rate of the satellite is required. The attached table shows the record of the use of these spin rockets.

(Table V)

In the case of TIROS II spin rockets were fired on ground command after as much as 10 months in space environment.

There has been developed, a partial control of the attitude of the satellite - also on ground command - by means of a magnetic orientation coil wrapped around the base of the satellite. In addition, for the successful operation of the infrared radiation detector system, lubricated ball bearings have to operate in space environment over a period of months.

Indeed from the point of view of an engineering development, the TIROS satellites are tremendously successful.

b. Second, the TIROS satellite measurements were found to contain much useful meteorological information. Fig. 10 shows examples of cloud patterns viewed by the TIROS satellites. These cloud patterns have been found to be related to, and characteristic of, the atmosphere in which they are embedded. In particular, cloud vortices were found to be the signatures of rotating storms. Fig. 11 is now a classic picture in the archives of meteorological satellite data results. Above is a mosaic of photographs viewed by TIROS I and below the clouds have been drawn in their proper geographic location. Superposed on the clouds are drawn the weather fronts of the day. The close relation between the cloud positions and the weather fronts is remarkable.

Fig. 12 shows other information produced by the TIROS satellites -- that of sea ice conditions. Note in the upper photograph, showing the mosaic of pictures taken on March 23, 1961, there was sea ice to the east (to the right) of Anticosti Island in the St. Lawrence River. Six days later on March 29 the same region was photographed by TIROS II and the area to the east of Anticosti Island is now clear of ice. Thus, the TIROS satellites have shown to yield valuable information on the formation, state and melting of sea ice.

Fig. 13 compares the infrared data taken by TIROS with the analysis of cloud heights as computed from reports of weather statinns over the U.S. In the upper photograph, the regions marked with "C" represent areas where the TIROS satellite measured cold cloud temperatures and the regions marked with "W" represent areas of warm cloud or ground temperatures. In the lower photograph, the areas of cloud heights are given in thousands of feet. Comparing the upper and lower photographs, we see that on the east coast, for example, the cold temperature regions measured by the TIROS satellites coincide with the regions of the very tall clouds, indicating that TIROS was measuring the temperatures of the tops of the clouds. There is also correspondence through the Plain States where the areas of warmer TIROS measured temperatures correspond to areas of low clouds or no clouds at all.

c. The third accomplishment of the TIROS satellites was that <u>this useful information was extracted and transmitted to weather services in time to be of value in weather analysis and forecasting</u>.

In anticipation of the possible utilization of TIROS data for immediate use by forecasters, teams of civilian and military meteorologists were stationed at the data acquisition stations, to study the incoming data in "real time". Within 60 hours after TIROS I was launched, picture data less than six hours old was being interpreted and analyses forwarded via facsimile transmission to the National Meteorological Center at Suitland. Fig. 14 shows how this picture information is analyzed in the form of a cloud analysis. Each enclosed area represents the analysis of the pictures taken by the satellite over that region.

Information such as this has been incorporated into the regular analyses and forecasts of the Weather Bureau; direct copies or coded representations are also relayed to our air and naval services both in this country and overseas, and to other national weather services where they prove to be very useful. These weather services have indicated that such cloud analyses:

> "establish, confirm or modify surface frontal positions; assist in the briefing of pilots on accurate weather; are used in direct support of overwater deployment and aerial refueling of aircraft; give direct support to the Anarctic resupply mission; confirm the position of Pacific typhoons; verify and amplify local analyses particularly over areas with few reports", etc.

The quality of the infrared (IR) radiation data has also been excellent. However, these data have to be reduced and plotted on maps before they can be properly interpreted. From this point of view, until rapid processing techniques can be developed, the IR data are not as useful as the picture data for immediate use by forecasters.

d. Fourth, there has evolved useful and active participation in international programs. From the very outset of the program, and reflecting the spirit of the very Act which gave birth to the NASA, the sharing of our results with other countries and working with them in this field have been active portions of our program. As has already been indicated, the analyzed results of the picture data are transmitted internationally to assist forecasters everywhere in describing and forecasting the weather. The basic observation data are made available to any foreign research group. Copies of the TIROS picture data may be acquired by any country in the form of 35-millimeter positive transparencies for projection or 35-millimeter duplicate negatives from the National Weather Records Center at Asheville, North Carolina.

Satellite information is more useful when combined with other meteorological observations, for example, special upper air soundings, aircraft observations, rocket observations, special radar coverage and others. Consequently, jointly with the Weather Bureau, NASA has contacted othermational meteorological services and have offered them the necessary satellite orbital information in the event they wish to make special observations which could be correlated with the satellite observations over their locality.

In November of last year an International Meteorological Satellite Workshop was conducted in which about 40 representatives of about 30 countries attended. The objective of the Workshop was to "present directly to the foreign weather services the results of the U.S. meteorological satellite activity to date and the possibilities for the future so that the program may be more completely known and understood by the scientific world community; that the present activity may be put in its proper perspective relative to future operational programs; and, finally, that the foreign weather services may acquire a working knowledge of the TIROS data for assistance in their future analyses programs, both in research and in operations and guidance in their own national observational support efforts". This workshop was an overwhelming success and now others are being planned to be held at periodic intervals.

e. Finally, there was yet another accomplishment. <u>A firm groundwork has been laid for the establishment of a National Operational Meteorological Satellite Systems(NOMSS)</u>. The operational utilization of the TIROS data captured the imagination of the weather services and made them all the more impatient for the establishment of an operational meteorological satellite system to provide such data continuously over the entire earth. Plans for the implementation of such a system were developed in the Spring of last year and the President requested Congress for funds to implement such a plan. Congress appropriated $48 million to the Weather Bureau for the implementation of this system. In its role as the national weather service, the Weather Bureau has general management responsibility for this system. More specifically, the Weather Bureau is responsible for coordinating the meteorological requirements of the weather data users, and for the meteorological data processing, analysis, dissemination and archiving. By transfer of funds from the Weather Bureau, NASA will develop the spacecraft, procure the launch vehicles, arrange for the launch, establish the ground stations, acquire the data, and transmit them to the National Meteorological Center.

9. Summary of Past Activities

a. The feasibility of a meteorological satellite as an engineering system has been demonstrated.

b. Important scientific measurements of the atmosphere have been taken.

c. Satellite measurements have been used in day-to-day weather analysis and forecasting operations.

d. An active international program of cooperation in meteorological satellites has been initiated.

e. A National Operational Meteorological Satellite System for providing satellite data on a regular basis for the use of weather services has been launched.

10. The Future Program

Now, what about the future?

The continuing long range goal of the national meteorological satellite program is to contribute to the understanding of atmospheric motions and processes both in the research sense and for the immediate daily use by the forecaster.

In order to proceed towards this long range goal the following seven immediate objectives have been established:

I. <u>To continue the extraction of scientific information from the satellite data.</u>

Much useful and new scientific information has been derived from the satellite data. However, this has involved only a very small fraction of the total data available. In order that they be more readily available for study the huge volume of data poured out by the satellites demands that these data be collected and stored in an orderly manner so that their recall can be rapid and systematic. Also, in the past the scientific investigation has been left more or less to its own devices, and progress was measured by the individual researcher's motivation. It would appear that with this large amount of new and valuable data becoming available that more deliverate and formal mechanisms be established to extract the useful scientific information from the data. Encouragement should be extended to these research groups where potential for growth in this area seems promising. Responsibility for the scientific analysis of these data should be extended to such groups.

II. <u>To improve the satellite itself as an observation platform</u>

The TIROS satellite, despite its extraordinary performance, is really a very simple and relatively unsophisticated satellite. It is relatively small -- 42" across and 19" tall and shaped like a pill box. Except for the base plate, it is entirely covered with solar cells which feed power to storage batteries. All the sensors are fastened to the base plate and the entire satellite is spin-stabilized.

The next generation of satellites - the Nimbus satellite -- will be larger and much more complex (Fig. 15). It will be about 10 feet tall and about 5 feet across at the base. It will consist of 3 relatively independent major subsystems. The solar paddles will rotate so as always to face the sun when the satellite is in sunlight and thus provide a more efficient utilization of the solar cells. The control system will stabilize the satellite relative to the earth. The sensory ring at the bottom has been designed on a modular concept so that modifications and changes in the experiments or subsystems that it contains can be effected without requiring a redesign of the entire spacecraft.

III. To increase the observational area coverage of the satellite

It has been estimated that the TIROS satellite views less than 25 per cent of the earth's surface over which it passes. The reasons for this low figure is explained below.

Fig. 16 shows the two features of the TIROS system which limit the spatial coverage. The first is the fact that originally TIROS was placed in an inclined orbit of approximately 48°. This means the polar regions are not readily available for observation. The second reason is due to the spin stabilization of the satellite with respect to space. This restricts useful observations only to those periods when the satellite is viewing the earth and the regions viewed are sunlit.

Due to the earth's oblateness the satellite's orbit plane precesses and associated with this precession there is a migration of the area favorable for picture taking from the northern hemisphere to the southern hemisphere and back again.

In order to increase the spatial coverage toward the poles the TIROS satellites after TIROS IV are being launched into a higher inclination orbit of 58°. The sea ice studies will also greatly benefit from this higher inclination orbit.

The true total coverage of the earth will not come about until the launch of the first Nimbus. Nimbus will have a 3-camera system and the area viewed by these cameras at any one time will be roughly 1500 miles by 500 miles. These dimensions will insure contiguous observations at the equator from one orbit pass to the next so that the entire earth will be viewed by the 3-camera system. Nimbus will be in polar orbit and thus will pass over every point on earth as the earth rotates beneath it. As stated earlier, Nimbus will be earth oriented and will always view the earth vertically (Fig. 16).

Table VI is a comparison wf the Nimbus and TIROS families. This table shows both the nature of the growth of the spacecraft and the increase in coverage as we proceed from TIROS to Nimbus.

(Table VI)

IV. To increase the frequency of observations over an individual area

The section above referred to the spatial coverage of the satellite. This section will refer to the time coverage.

Fig. 17 shows the time coverage problem that has existed for the TIROS satellite, Here are depicted selected orbits of TIROS in relation to readout stations at Wallops Island and the Pacific Missile Range. Each circle surrounding the two readout stations represents the area where contact can be made by the readout station with the satellite. You will note that orbits B, C and D all lie outside of these intercept circles. In all, there are six to seven such orbits so that under the most favorable conditions we are able to read out only eight of the possible fourteen orbits of TIROS by means of our two Command and Data Acquisition (CDA) stations. Thus, while some areas may be read out on successive days some cannot be read out at all for long periods at a time. We have added a clock start capability at Santiago, Chile which permits us to select a particular one of the seven orbits for storage and later readout. However, it does not increase the number of orbits read out.

Nimbus, on the other hand, will be in polar orbit. Fig. 18 is a polar projection with the North Pole in the center of the figure. It shows the possible 14 daily orbits of Nimbus relative to the established CDA station at Fairbanks, Alaska. All but four orbits are available to this station. The addition of another CDA station in Northeastern North America will permit the acquisition of practically all the orbits every single day. Thus, every point on earth will be covered at least once every 12 hours, once in the daytime and once at night. In the polar regions the frequency of observations will be much greater.

This frequency of observations unfortunately is still not adequate.for some meteorological problems. Fig. 19 illustrates diagrammatically some properties of various scales of atmospheric systems. The vertical axis is a measure of the typical size of a weather system in miles on a linear scale and the horizontal axis is a measure of the lifetime of the weather system in hours on a logarithmic scale. Notice that cyclonic storms are quite large and last many days. Hurricanes are smaller and their duration is less. Tornadoes on the other hand are of a very small size and have extremely short duration -- on the order of minutes. With one Nimbus satellite aloft, hurricanes and larger storms will readily be observed. Two Nimbus satellites, providing local observations every 6 hours, would improve matters only slightly. The severe storms, thunderstorm cells, and tornadoes whose lifetime is less than 5 hours could develop and dissipate entirely between two successive observations in the Nimbus system. Thus, what is required is a more continuously observing satellite.

Fig. 20 shows the current thinking with regard to a possible satellite of this kind. This satellite is still in the study stage and does not constitute an approved NASA program. It will be launched into a synchronous orbit, i.e., an equatorial orbit, and will appear to remain stationary over the subsatellite point. Its sensors will give gross observations of the earth's cloud cover and detailed observations of selected areas of potential or observed storm activity.

V. To continue the development of new flight sensory systems

An important part of the NASA Research and Development Program is to continue the search for useful meteorological sensors to fly onboard the meteorological satellites. Because, characteristically, meteorological satellites can view the atmosphere only at a distance, one must rely entirely on the measurements of radiations from the atmosphere. Thus, for the new sensor development one must search in the electromagnetic spectrum for regions in the spectrum that are related to the physics of the atmosphere. So far the visible region and certain IR radiation bands have been utilized. There is work going on in the study of CO_2 absorption bands, the microwave region and in the ultra-violet. For each of these significant radiation regions, suitable flight hardware has to be developed. Areas for development include: TV vidicons, electrostatic tape cameras, image orthicon cameras, improved IR radiation detectors, IR spectrometer, radar and sferics.

Nimbus has been deliberately designed to readily accept these new sensors as they become developed without requiring a complete redesign of the satellite.

VI. <u>To continue to provide data from meteorological satellites in orbit for real time use by the forecaster</u>

As was mentioned above, within a very short time of the launch of TIROS I, the data produced by this experimental satellite was transmitted to field users. This operational use of the TIROS data has continued and has improved. The number of instances where this data has been helpful to the forecaster in his analysis of existing weather data are too numerous to mention and have been well documented elsewhere. A few dramatic applications to forecasting will be indicated, however.

Fig. 21 shows the photographs which TIROS III took of the first 5 hurricanes of the 1961 season. The identification and tracking of hurricanes are very important activities of the Weather Services.

Fig. 22 is a global cloud analysis for September 11, 1961. This is a northern hemisphere polar projection. The cross in the center represents the North Pole. Each of the swaths represents the analysis of one TIROS orbit. The data show that in one day TIROS viewed 5 individual hurricanes in the region from North America to Europe, as well as typhoons Nancy and Pamela in the Pacific. It is not known whether storms of such proportions existed in the remainder of the areas since it is not possible to read out every TIROS orbit. Information such as this is provided immediately to the forecast centers for their use in charting the weather events.

For maximum real time use of the data, solutions must also be found for optimum methods of data presentation and transmission from the satellite to the CDA station from the CDA station to the weather central and finally from the weather central to the user. Methods must also be found for data compression and perhaps also for onboard data analysis in order to reduce the quantity of data being transmitted along the communications channels.

VII. <u>To increase the scope and extent of international participation</u>

With a full realization that the atmosphere is a global phenomenon and that the fulfillment of any one country's responsibilities in meteorology is closely linked to the extend that it participates with other countries in similar activities, work is continuing actively in the direction of the development of a comprehensive international program. In addition to the activities already described and including:

A. Transmission of cloud analysis

B. Provision of satellite data through the National Weather Records Center

C. Encouragement of supporting observations

D. Sponsoring international workshops

there are active plans with regard to two other activities.

E. <u>Planning for ultimate direct readout</u>

(1) Increased numbers of complete readout stations: Currently the number of possible readout stations is limited by the available power on board the satellite and the fact that readout currently erases the taped data. With the development of a non-destruct readout capability and proper programming of power it will be possible to increase the number of primary readout stations. Other countries willing to make such a major installation will be able to interrogate the satellite and read it out without destroying the contents on board the satellite.

(2) Automatic Picture Transmission: A recent technological development will permit flying onboard a forthcoming satellite a special vidicon camera system which can operate automatically and continuously in sunlight. This camera system has a "sticky" vidicon which after taking a picture stores it long enough to permit a slow readout (3 min.) of the data by an electron beam. This slow readout and associated transmission permits the simplification of the associated ground equipment (price estimated lower than $50,000). Thus, any country will have in its

reach the ability to acquire directly from the satellite facsimile quality pictures of the local cloud cover within a range of about 1000 miles (Fig. 23).

F. Planning for a global operational system

A start in this direction has already been made as a result of UN Resolution 1721 and the bilateral discussions being conducted by the U.S. and USSR resulting from the exchange of notes between President Kennedy and Premier Krushchev.

TABLE I

TIROS Television Camera Parameters

Parameter	Wide-Angle Camera	Medium-Angle Camera	Narrow-Angle Camera
Picture size, miles (400-mile orbit, camera vertical)	700 by 700	420 by 420	70 by 70
Lines per frame	500	500	500
Frames per second	0.5	0.5	0.5
Video bandwidth, kc	62.5	62.5	62.5
Pictures per orbit (stored)	32	32	32
Overlap between pictures in the direction of vehicle motion, per cent	75	10	None
Peak power, watts	9	9	9
Lens	104° f/1.5	76° f/1.8	12.67° f/1.8
Shutter speed, millisec.	1.5	1.5	1.5

TABLE II

TIROS Command and Data Acquisition (CDA) Stations

TYPE	TIROS I-II	TIROS III-VI
Primary	Ft. Monmouth, N.J.	Wallops Island, Virginia
Primary	Kaena Point, Hawaii	Pacific Missile Range, California
Backup	Princeton, N.J. (RCA)	Princeton, N.J. (RCA)
Auxiliary	--	Santiago, Chile

TABLE III

TIROS Characteristics

	I	II	III	IV	V	VI
Size	42"x19"	42"x19"	42"x19"	42"x19"	42"x19"	42"x19"
Weight (lbs.)	263	278	285	287	286	281
TV Cameras *	NA WA	NA WA	WA WA	WA MA	WA MA	WA MA
IR Sensors *	-	S,W	S,W,O	S,W,O	-	-
Magnetic Altitude Control	-	Yes	Yes	Yes	Yes	Yes
Beacon Frequency (mc)	108	108	108	136	136	136(1)
TV Picture Frequency (mc)	235	235	235	235	235	235
IR Data Frequency (mc)	-	237	237	237	-	-

*NA: Narrow angle (12°); WA: Wide angle (104°); MA: Medium Angle (76°)
S: Five channel scanning radiometer
W: Wide field directional radiometer
O: Omni directional wide field radiometer
(1): One year timer to silence beacons added

TABLE IV

TIROS Launch Data

	I	II	III	IV	V	VI
Launch date	4-1-60	11-23-60	7-12-61	2-8-62	6-19-62	9-18-62
Designation	1960 Beta 2	1960 Pi 1	1961 Rho 1	1962 Beta 1	1962 Alpha-Alpha 1	1962 Alpha-Psi 1
Launch Vehicle	Thor-Able	Thor-Delta	Thor-Delta	Thor-Delta	Thor-Delta	Thor-Delta
Period (min)	99.2	98.3	100.4	100.4	100.5	98.7
Inclination (deg)	48.4	48.5	47.8	48.3	58.1	58.3
Perigee (st. miles)	429	387	461	441	367	425
Apogee (st. miles)	466	453	506	525	604	442
Eccentricity	.004	.007	.005	.009	.027	.002
Useful Operating Lifetime (mos)	2 1/2	10	4 1/2	4 1/2	*	*

*Still providing useful data

TABLE V

TIROS Spin Control Performance

	TIROS I	TIROS II	TIROS III	TIROS IV	TIROS V	TIROS VI
Launch date	4-1-60	11-23-60	7-12-61	2-8-62	6-19-62	9-18-62
Injection spin-up rate, rpm	84	120	115	(108)	(108)	100
Final despin rate, rpm	10	8	9.4	8.3	8.3	7.0
1st Spin-up						
Date	5-27-60	11-25-60	8-8-61	4-24-62	6-26-62	9-20-62
Orbit No.	819	31	368	230	104	33
Initial and final rpm	9.5 to 12.85	8 to 10.9	9.11 to 12.78	8.22 to 9.79	8.26 to 11.71	6.9 to 10.6
Change in rpm	3.35	2.9	3.67	1.57	3.45	3.7
2nd Spin-up						
Date	8-18-60	11-25-60		2-25-62		
Orbit Number	1.975	35		244		
Initial and final rpm	11.76 to 13.47	10.9 to 13.37		9.79 to 11.72		
Change in rpm	1.75	2.97		.3		
3rd Spin-up						
Date		9-23-61		5-27-62		
Orbit Number		4,467		1,555		
Initial and final rpm		8.6 to 9.25		10.31 to 13.34		
Change in rpm		0.56		303		
4th Spin-up						
Date		9-28-61				
Orbit Number		4,537				
Initial and final rpm		9.13 to 11.18				
Change in rpm		2.05				

TABLE VI

Comparison of Nimbus and TIROS

	TIROS	Nimbus
Geometry	Pillbox	Dumbbell
Weight (lbs)	300	650
Orbital Altitude (nautical miles)	380	600
Orbital Inclination	48° (I-IV) 58° (V-)	80° Polar, Retrograde
Stabilization	Spin-Stabilized	3-Axes Earth Oriented
Earth Coverage (%)	10 to 25	100
Camera Raster	500 lines/frame	800 lines/frame
TV Resolution (Miles)	1	1/2
Maximum Power Available (Watts)	20	400
IR Sensors (resolution, miles)	MRIR (30)	MRIR (30) HRIR (5)

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Figure Legends

Fig. 1 World Radiosonde Network

Fig. 2 World separated into 100 equal areas showing number of upper air stations in each area. (WMO study)

Fig. 3 First pictures taken from "space" of earth's cloud cover. V-2 rockets pictures of March 7, 1947. A film recovery system was used.

Fig. 4 Explorer VI transmits the first "TV pictures" from space, August 7, 1959. The picture on the left is a reproduction of the data transmitted. On the right is shown the geographic area to which it applies plus the observed cloud cover.

Fig. 5 TIROS I is launched by a Thor Able on the morning of April 1, 1960, from Cape Canaveral.

Fig. 6 Cutaway view of TIROS Spacecraft.

Fig. 7 Spin up rocket arrangement on the bottom of the TIROS baseplate.

Fig. 8 Measurements derived from detectors of TIROS five channel radiometer.

Fig. 9 TIROS infrared electronics equipment.

Fig. 10 Cloud patterns viewed by TIROS satellites.

Fig. 11 Storms and fronts; a family of weather systems. Top, mosaic of TIROS photographs; bottom, weather map, May 20, 1960, with TIROS cloud data.

Fig. 12 TIROS II sea-ice data.

Fig. 13 Map (top) of TIROS II infrared data and (bottom) cloud analysis (~~bottom~~) simultaneous with infrared data.

Fig. 14 Detailed cloud analysis, September 11, 1961.

Fig. 15 Nimbus meteorological satellite.

Fig. 16 (Left) TIROS in inclined orbit and space oriented; (right), Nimbus in near polar orbit and earth oriented.

Fig. 17 Selected orbits of TIROS in relation to readout stations at Wallops Island and the Pacific Missile Range.

Fig. 18 Nimbus orbital paths relative to Fairbanks Command and Acquisition Station, acquisition range. Northern Hemisphere in polar projection.

Fig. 19 Lifetime of typical weather systems.

Fig. 20 Synchronous meteorological satellite.

Fig. 21 TIROS III hurricane data.

Fig. 22 Global cloud analysis, September 11, 1961, Northern Hemisphere in polar projection.

Fig. 23 TIROS test of the Automatic Picture Transmission Subsystem. TIROS is shown passing across central U.S. and transmitting automatically to many locations having a simplified ground station shown below. Regular TIROS pictures both stored and taped are shown being transmitted to the primary CDA installation on the East Coast. The other CDA station is shown on the West Coast.